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Field Monitoring of Solar Domestic Hot Water Systems Based On Simple Tank Temperature Measurement

Jay Burch
Yuantao Xie
National Renewable Energy Laboratory

Clifford S. Murley
Sacramento Municipal Utility District

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National Renewable Energy Laboratory
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Golden, Colorado 80401-3393
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Jay Burch
Yuantao Xie
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401

Clifford S. Murley
Sacramento Municipal Utility District
PO Box 15830
Sacramento, CA 95852-1830

ABSTRACT

By dynamically measuring solar storage tank temperature(s), the solar storage tank effectively becomes a dynamic calorimeter to measure the energy flows in a solar system. The energy flows include solar loop gain, tank losses, and potentially draw extraction. With one-channel temperature loggers storing data over several days to several weeks, this approach provides low-cost, modest-accuracy performance assessment, useful for determination of savings persistence and diagnostics. Analysis is based upon the tank energy balance, identifying solar gain during the day and tank losses at night. These gains and losses can be compared to expectations based upon prior knowledge, and estimated weather conditions. Diagnostics include controller and pump operation, and excessive nighttime losses. With one point temperature logger, solar gain accuracy is expected to be 20 to 50%, depending on draw frequency and volume. Two examples are shown, a properly operating system and a system with excessive nighttime losses.

INTRODUCTION

Objectives in field monitoring of solar domestic hot water systems (SDHWS) include direct measurement of energy savings, model validation, persistence of savings or reliability, and system diagnostics. Although limited diagnostics will follow naturally from this methodology, the objective prompting this work is *reliability:* determine for an ensemble of specific systems what fraction of the potential savings on average is actually realized over time. For reliability monitoring, it is necessary to have relatively large sample sizes. For example, if one wishes to infer that at least 90% of the systems are operating with 90% confidence, then about 22 random samples per system model are required at various times over the ensemble's lifetime. Low-cost metering is essential. An envisioned application of the technique discussed in this paper is as follows: SDHWS maintenance contractors install simple loggers during routine site visits, the logger is mailed by the homeowner to an analyst, and the results feed into a national reliability data base establishing savings persistence. The accuracy required for reliability monitoring is less than that required for model validation or direct performance determination. If the minimum objective is to identify whether the system is in "working" or "non-working" categories, then a measurement of solar savings to about 50% is adequate. There are several approaches to low-cost reliability monitoring (1). The focus here is on a direct approach, measuring the tank temperature and directly inferring the solar storage gain and losses, using the storage tank as a calorimeter.

Tank temperatures are commonly used in SDHWS monitoring. The Solar Rating and Certification Corporation requires a temperature probe in the top of the solar tank (2). The temperature at the top of the solar tank is a good indicator of system operation, especially for well-mixed systems. The method discussed in this paper is basically a quantitative use of tank temperature data. In (3), temperatures at the top of the tank, and on the solar loop supply and return were used. Temperatures were logged with small data loggers about once every 10 minutes. The loggers operated several weeks, and data was examined visually for expected heat-up patterns and temperature differences. Malfunctioning of the recirculation controller at night was detected in one case. The method in this paper similarly logs tank temperatures, with the addition of quantitative comparison to expected performance. The approach of measuring tank average temperature by attaching probes to tank wall, and using the tank as a calorimeter was used in (4). That study was on a high-flow system under conditions of no draw and an isothermal start, and the objective was to determine the HWB model representing the system. It was also shown that a correction to the temperature should be applied, particularly for dynamic analysis, as there are offsets and delays in the temperature response due to attaching probes to the tank wall. Similar corrections are needed in this study, although dynamics are not generally important.

The experiment installation used here is particularly simple, taking several minutes per sensor. Tank temperature can be measured in several ways, including use of point probes (like thermistors) on the side of the tank, or immersed line-averaging probes (like the RTDs used in HVAC duct measurements). There are distinct advantages to using averaging probes. For this work, discrete temperature probes are attached to the side of the tank. To avoid excessive temperature offset between tank wall and water, it is necessary that insulation cover the probe and surrounding tank wall; the typical tank insulation (typically 3 to 5 cm.) is usually sufficient. Thermal grease is applied and the greased probe is taped securely to the tank wall. In this study, an access port just below mid-height of the solar storage was typically used, and covered with fiberglass insulation. A small hole could be drilled though the outer steel jacket, if necessary. Low-cost ($120) temperature data loggers holding 8000 data points at user-specified averaging intervals were used, with storage intervals typically set to about 3 minutes. In the remainder of this paper, the focus is on the analysis methods and results from two field installations.

THEORETICAL BASIS

A correctly operating solar system shows certain characteristic tank temperature patterns, as shown in Fig. 1. There will be temperature increase during the day (0-45C, depending on draw), and temperature decrease at night (several degrees per hour, depending on environmental temperature). These qualitative observations are sufficient for identifying the system as functioning or not. For more quantitative analysis, we can derive the tank loss coefficient (which will indicate anomalous nighttime losses), determine the controller on times, and compare net daytime energy gain to an expectation dependent on operating conditions. Consider an energy balance on the solar energy storage, as shown in Fig. 2. The dynamic balance can be stated as:

$$(1)\quad \dot{Q}_{solar} + \dot{Q}_{draw} + \dot{Q}_{loss} = \dot{Q}_{int} = (V_{tank} \cdot C_{vol}) \cdot \dot{T}_{tank}$$

where:

Q_{solar}= solar loop energy
Q_{draw} = draw energy = $C_{draw}(T_{out} - T_{in})$
Q_{loss} = tank loss = $UA_{tank}(T_{env} - T_{tank})$
Q_{int} = internal energy = $V_{tank}C_{vol}(T_{tank})$
V_{tank} = tank volume
C_{draw} = draw capacitance flow rate
T_{env} = tank environment temperature
T_{tank} = average tank temperature
V_{tank} = tank volume
C_{vol} = volumetric heat capacity
˙ over symbol denotes time derivative

By measuring tank temperature dynamically, and computing temperature derivative, the Q_{int} term can be calculated if V_{tank} is known. V_{tank} can be taken from nameplate rating, to an accuracy of +0,-10%. (Better accuracy can be achieved using measured volume, if available.) The energy balance thus provides direct measurement of (Q_{solar} + Q_{draw} + Q_{loss}), and the problem becomes how to separate these terms.

Tank loss calculations

It is reasonable to analyze late-night periods when the solar loop is not operating, and to assume that there is no draw. In this case, the typical nighttime temperature decays as shown in Fig. 1 provide the basis for analysis. Qualitatively, a decay of several degrees per hour is "normal" behavior. Quantitatively, one can calculate UA_{tank}, given T_{env} estimate. If a probe is attached to the tank inlet or outlet piping, we can usually infer T_{env}, when the pipe has equilibrated with the environment. (Such a probe can also be used as a draw indicator, see below.) From the temperature decay between time t_1 to t_2, UA_{tank} is inferred assuming constant T_{env} (the analysis is easily generalized for varying T_{env}):

$$(2)\quad UA_{tank} = \frac{C \cdot \ln\left[\left(T_{tank}(t_1) - T_{env}\right) / \left(T_{tank}(t_2) - T_{env}\right)\right]}{t_2 - t_1}$$

This value can be compared to a general expectation, e.g., about two to five times the value based upon nominal tank insulation. When this value is not within these bounds, one can hypothesize that the check valve has failed, the pump is operating at night (controller failure), insulation is missing or defective, or that a small, steady draw (e.g., leading faucet) is present. For antecedent solar analyses, one can now consider Q_{loss} a known correction term in the energy balance.

Solar calculations

There are two useful data analysis approaches: dynamic and integrated. The dynamic approach is based directly upon Eqn. 1, with direct computation of the time derivative of T_{tank} (with suitable smoothing on the order of one hour) providing dynamic net energy gain. An example is shown in Fig. 3. Integrated analysis is based on integration each day of Eqn. 1 from the beginning to the end of solar operation, t_{begin} to t_{end}:

$$(3) \quad Q_{solar} + Q_{draw} = V_{tank}C_{vol}\left[T(t_{end}) - T(t_{begin})\right] - Q_{loss}$$

The times t_{begin} and t_{end} are detected by searching for the first and last times of positive temperature derivative between sunrise and sunset. In either case, the average value of (t_{end} - t_{begin}) should be a reasonable fraction of the sunrise to sunset time, as a diagnostic of controller operation.

The unpredictable draws inherent in field data are a fundamental complicating factor: in principle, only the sum ($Q_{solar} + Q_{draw}$) can be inferred. When draws are present, ($Q_{solar} + Q_{draw}$) < Q_{solar}, since Q_{draw} <0. With point probes, it may be useful to place a "draw indicator" temperature probe on a inlet or outlet pipe, which would indicate when long and/or frequent draws were occurring. Problems can arise due to thermosiphoning from the hot tank, dictating careful placement of the probe. If $T_{tank,out}$ is monitored, it serves triple duty as a draw indicator, draw temperature probe, and Tenv probe, as shown in Fig. 4. Presence of draws are detected by sharp changes in the temperature. When draws are unknown (as with one probe case), the net expected ($Q_{solar} + Q_{draw}$) should be a continuum from zero (or even negative) to some upper bound corresponding to Q_{solar} on a clear day with no draws.

A system model is necessary to provide a normalized expectation of daytime performance. The normalization accommodates the fact the performance will certainly depend upon system characteristics (e.g., collector size), weather (e.g., irradiance), and system operating temperature (e.g., dependent upon draw). In general, the geometry and characteristics of the system can be assumed known from observation at the site, although there can be ambiguities (e.g., absorber type). The model complexity can vary from a simple collector model to a dynamic component simulation model; the appropriate choice would appear to depend upon accuracy desired and availability of weather data. There are probably two useful model-analysis combinations: dynamic model and dynamic analysis, or integrated analysis with simple collector model.

Simulation and dynamic analysis is the most complex, but potentially yields the highest density of data points to assess system operation. This is most useful when draws are frequent. Dynamic weather data is needed to drive the model for dynamic comparison. Highest accuracy would be achieved when a nearby location provides weather data. In the likely event no such data is conveniently available, one would have to make approximate estimates, and realistically restrict detailed analysis to mostly clear periods, when irradiance is reasonably estimated. Cloud cover and ambient temperature can be determined from occasional observation near the site, or from newspaper reports.

A simple collector model combined with integrated data analysis appears best when no weather information is available easily. This method is chosen for the examples presented below. The sum of ($Q_{solar} + Q_{draw}$) computed via Eqn. 3 can be compared to the daily expected Q_{solar} based upon estimated temperature and irradiance, as shown in Fig. 5. In this comparison, we first cast the calculated net energy gain into a "clear day efficiency", defined as dividing the net collected energy by expected clear day collector incidence; this allows direct comparison to the collector model, as an upper bound. The collector operating parameter $T^* = (T_{inlet} - T_{ambient})/I_{incident}$ is taken as an irradiance-weighted daytime average value. The T_{inlet} value is taken as the measured tank temperature, possibly with an offset based on estimated heat exchanger effectiveness. The daytime average T^* value should be weighted toward noon-time values, where incidence angles are smallest and energy collection is largest. In the examples below, the average T_{inlet} value was taken as the mid-day value, and irradiance average was taken as 631 W/m^2 (200 BTU/h-ft^2).

Error estimation

Error estimation depends on the data available and the analysis approach chosen. Error is illustrated for the approach of a simple collector model used with integrated analysis, and we treat two cases of tank temperature approach: a) a single mid-tank temperature probe; and b) a line-averaging probe. Estimated errors in the quantitative analysis are shown in Table I, starting with independent variables and proceeding through derived quantities. With a single temperature probe, error estimate for average tank temperature is difficult, due to draw-induced stratification affects. It is possible, for example, that a combination of draws and solar operation could occur which result in little change of the measured tank mid-point temperature, and net energy calculated is quite erroneous (100% error!). Such occurrences are expected rarely, as seen in the examples and as expected from typical residential draw patterns dominated by morning and evening draws, especially for weekdays. The 10 °C error in temperature change is a conservative estimate, based on estimates of stratification affects potentially dominating roughly 1/3 the time (weekends). For the line-averaging probe, the presence of draws are detectable, and stratification has no significant affect in the analysis. The error in UA_{tank} is dominated by error in estimate of T_{env}, of about 5 °C. Accuracy would be increased by installation of a sensor (such as on the outlet pipe) which gives some measurement of T_{env}.

TABLE 1. ERROR ANALYSIS

Variable	Point probe	Line-average
T_{end} - T_{begin}	10 °C	2 °C
V_{tank}	5%	5%
$\eta_{measurement}$	30%	11%
UA_{tank}	70%	60%
$T_{col.\ inlet}$, $T_{ambient}$	5 °C	5 °C
$I_{clear\ day}$	15%	15%
T^*	50% (typ.)	50% (typ.)
η_{model}	11%	11%
$\eta_{total.}$	32%	16%

The error in the calculated value of the daily average operating parameter $T^*=(T_{inlet} - T_{ambient})/I_{incident}$ is about 50%, at typical operating conditions for the examples below. This uncertainty propagates to about 4% uncertainty in efficiency, which is about 11% of the energy collected. The model error is reduced when measured weather data is available. If the model error is added in quadrature with the measurement error, the total efficiency error is roughly 30 to 40% in the case of the point probe, or about 10-20% for the line-average case.

EXAMPLES

During September 1994, three systems installed under the Sacramento Municipal Utility District Solar Program (5) were monitored for 17 days each (logger capacity at 3 min. storage intervals). The weather was mostly clear and warm, highs ranging from 25°C to 35°C. Two indirect glycol loop systems with a wrap-around tank-heat exchanger, and a drainback system were monitored, in all cases with multiple probes to test sensitivity to number of probes. Software to perform the analyses described above was written, and a standard report format was developed to provide detailed results for the entire data sets. In all cases, the conclusions reached based upon a single probe at mid-height of the solar storage were equivalent to conclusions with large number of probes, and it was concluded that use of a single probe appears adequate. Partial results are reported here based upon data from a single probe installed near mid-height of the solar storage, and estimated ambient temperature based upon long term average weather.

Tank temperature data for site 1 are shown in Fig. 1. The average value for UA_{tank} was 7.8 +/- 5 W/°C. The nominal value for UA_{tank}, derived from the manufacturer's quoted R value, is 1.8 W/°C. The measured UA_{tank} is about 4 times the nominal value, well within usual bounds. The controller was on about 7 hours per day, which is about 60% of the sunrise/sunset time. This is a reasonable figure for mostly clear weather. The values of (Q_{solar} + Q_{draw}) inferred from the daytime temperature change ranged from 7.7 to 35.7 MJ/day (7.3 to 34 kBTU/day). The daily "clear day efficiency" points are shown against the collector efficiency plot in Fig. 5. It can be seen that most of the points fell significantly below the collector curve, with some approaching the curve. This is indicative of normal daytime solar collection. There was not much variation in the daily operating conditions, as seen by the lack of spread in the data points.

Tank temperature data for site 2 are shown in Fig. 6. By comparison of site 2 with site 1 temperature data, it can be noted that both site show large increases during the day, but site 2 shows very high temperature decrease at night. The average value for UA_{tank} was 19.3 +/- 5 W/C. The same tank was present at site 2 as for site 1. In this case, however, the measured value for UA_{tank} is about 11 times the nominal value, which indicates a problem with nighttime losses. Further investigation will be done to determine the cause (most likely mixing valve failure, as the owner did not notice the motor running at night). As far as solar operation is concerned, it is important to note that this system showed quite normal operation. The controller on-time and comparison to collector efficiency were all quite within expected bounds, similar to site 1. Nonetheless, net savings from this system are significantly below potential, depending on use patterns (which affect the solar energy needlessly lost before usage the following morning).

CONCLUSIONS

A method of field monitoring based upon tank calorimetry has been introduced. The method is potentially useful for diagnostics, and for reliability monitoring, where low resolution of energy flow is adequate, and costs must be kept very low. A single channel logger will be quantitatively adequate in cases where the storage tank is accessible, and higher accuracy is achieved when the tank is relatively well-mixed. Accuracy is in the 20-50% range for a single point probe, depending upon draw and system stratification.

Uncertainty can be reduced to 10-20% range by using multiple point probes or a line-averaging probe. Accuracy is also increased when weather is based upon measurement or observation, and when a draw probe is utilized.

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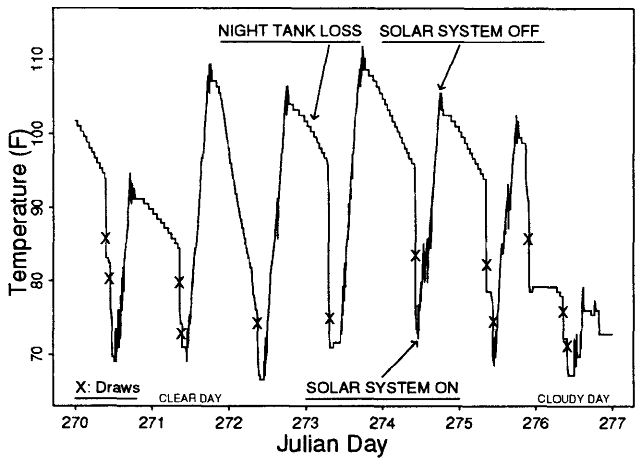

Fig. 1 Tank temperature versus time at site 1. The probe was located near the middle of solar storage.

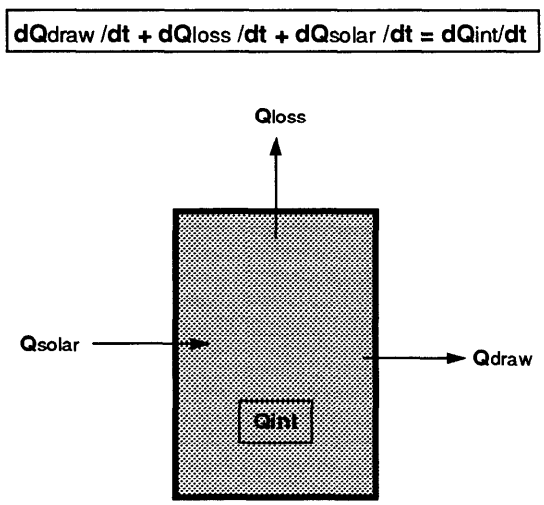

Fig. 2 Tank energy balance, showing energy gains and losses for the solar storage. In one-tank systems, the control volume is drawn below the auxiliary storage.

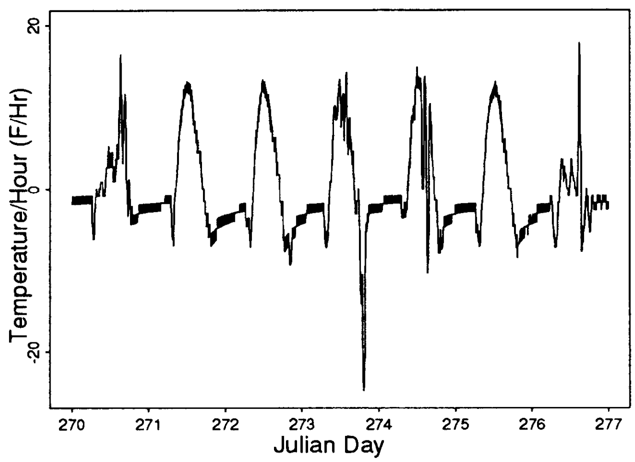

Fig. 3 Tank temperature time derivative versus time for 7 days of data at site 2. For most clear days, there seems to be little evidence of draw, except for day 273.

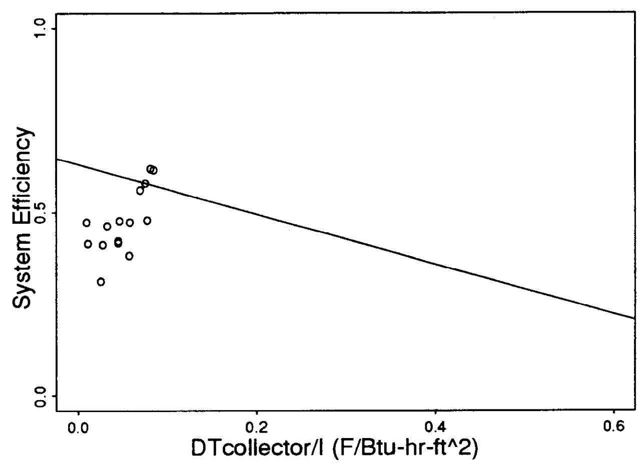

Fig. 5 Collector efficiency versus collector operating parameter T^*. Data points displayed as open circles are the daily clear day efficiency, calculated as explained in the text.

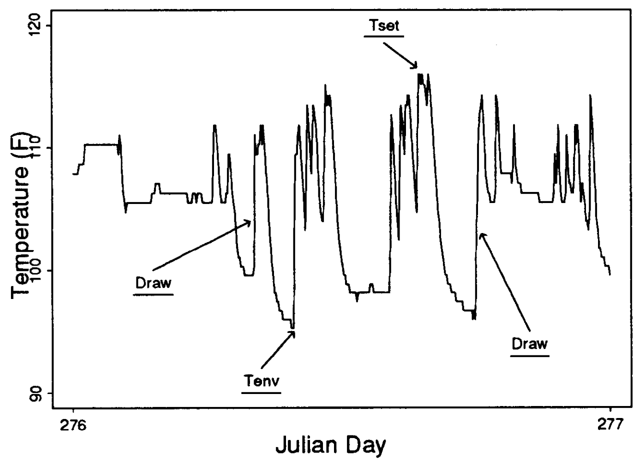

Fig. 4 Tank outlet pipe temperature versus time for site 4. The figure indicates that rapid temperature increase implies a draw is occurring, that equilibrium temperature provides a measure of T_{env}, and that the maximum temperature after a draw indicates the tank outlet temperature.

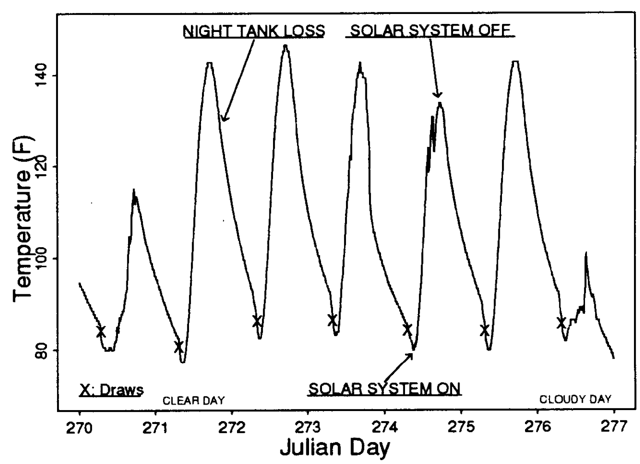

Fig. 6 Tank temperature versus time at site 2. The probe was located near the middle of solar storage, identically to site 1. Compare the rapid nighttime decrease in decrease of site 2 versus that of site 1.